

# Novel Transversity Properties in SIDIS

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**Abstract.** We consider a rescattering mechanism to calculate a leading twist  $T$ -odd pion fragmentation function, a candidate for filtering the transversity properties of the nucleon. We evaluate the single spin azimuthal asymmetry for a transversely polarized target in semi-inclusive deep inelastic scattering (for HERMES kinematics) and the double  $T$ -odd  $\cos 2\phi$  asymmetry in this framework.

## Introduction

The transversity distribution,  $h_1$  which measures the probability to find a transversely polarized quark in the transversely polarized nucleon, is as important for the description of the internal nucleon spin structure as the more familiar helicity distribution function,  $g_1$ . However, it still remains unmeasured, unlike the spin-average and helicity distribution functions, which are known experimentally and extensively modeled theoretically. The difficulty is that  $h_1$  is chiral odd, and consequently suppressed in inclusive deep inelastic scattering (DIS) processes [1]; it has to be accompanied by a second chiral-odd quantity. Semi-inclusive deep inelastic scattering (SIDIS) on polarized nucleons is one of several [2, 3, 4] promising methods proposed to access transversity. It relies on just such a quantity the so called Collins fragmentation function [5], which correlates the transverse spin of the fragmenting quark to the transverse momentum of the produced hadron. Beside being chiral-odd, this fragmentation function is also time-reversal odd ( $T$ -odd) [6, 7] which makes its calculation challenging. In this context, the non-zero single spin asymmetries in recent measurements [3] may signal the existence of a non-trivial  $T$ -odd effects which are intimately tied to our understanding of transversity. Here we explore [8] a one-gluon exchange mechanism, for the fragmentation of a transversely polarized quark into a spinless hadron similar to the approach we applied [9, 10] to the distribution of the transversely polarized quarks in the both unpolarized and transversely polarized nucleons. The non-perturbative information about the quark content of the target and the fragmentation of quarks into hadrons in SIDIS is encoded in the general form of the factorized cross sections in terms of the quark distributions  $\Phi(p)$  and fragmentation functions  $\Delta(k)$ , entering the hadronic tensor. To leading order in  $1/Q^2$  [11] the fragmentation functions are projected from

$$\Delta(k, P_h) = \sum_X \int \frac{d\xi^+ d^2\xi_\perp}{2z(2\pi)^3} e^{ik \cdot \xi} \langle 0 | \mathcal{G}_{[\xi^+, -\infty]} \psi(\xi) | X; P_h \rangle \langle X; P_h | \bar{\psi}(0) \mathcal{G}_{[0, -\infty]}^\dagger | 0 \rangle \Big|_{\xi^- = 0}. \quad (1)$$

Here  $k$  quark fragmenting momenta and  $P_h$  is the fragmented hadron momenta. The path ordered exponential along the light like direction  $\xi^-$  is

$$\mathcal{G}_{[\xi^-, \infty]} = \mathcal{P} \exp \left( -ig \int_{\xi^-}^{\infty} d\xi^- A^+(\xi) \right).$$

In non-singular gauges [12, 13], the gauge link gives rise to initial and final state interactions which in turn provide a mechanism to generate leading twist  $T$ -odd contributions to both the distribution and *fragmentation* functions. The joint product of these functions enter novel azimuthal asymmetries and single spin asymmetries (SSAs) that have been reported in the literature [14, 15, 9, 10]. Such an analysis was recently applied to the  $T$ -odd  $f_{1T}^\perp$  [14, 13, 16] and  $h_1^\perp$  [15, 9, 10] distribution functions in addition to  $T$ -odd baryon fragmentation functions [17]. We apply [8] an analogous procedure to generate the  $T$ -odd pion fragmentation function,  $H_1^\perp(z)$  (see also [18]).

### Pion Fragmentation Function

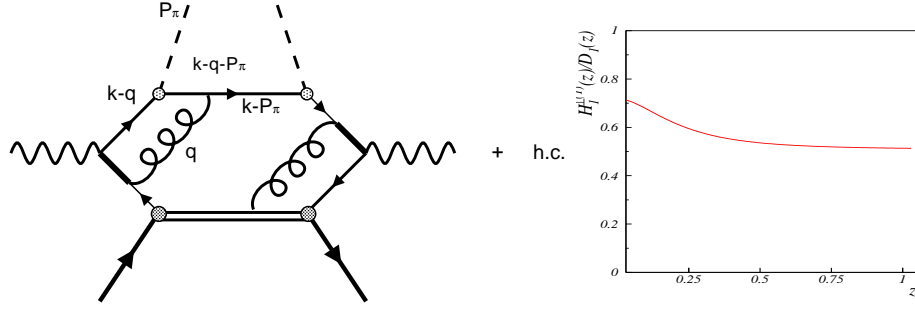
The leading order contributions to the  $T$ -odd fragmentation functions come from the first non-trivial term in expanding the path ordered gauge link operator. The corresponding Feynman rules are those for interactions between an eikonalized struck quark and the remaining target [19] depicted in Fig. 1. In modeling the highly off-shell fragmenting quark we adopt a minimal spectator [20] approach. We couple the on-shell spectator, as a quark interacting with the produced pion through a Gaussian distribution in the transverse momentum dependence of the quark-spectator-pion vertex [10, 8] in order to address the log divergence arising in the moments of fragmentation functions. The leading order (in  $1/Q$ ) one loop contribution which arises in the limit that the virtual photon's momentum becomes large corresponding to the rescattering of the initial state quark depicted in Fig. 1. The resulting twist 2,  $T$ -odd contribution the fragmentation function [8] projected from  $\text{Tr}(\gamma^- \gamma^\perp \gamma_5 \Delta)$  is

$$H_1^\perp(z, k_\perp) = \frac{\mathcal{N}'^2 f^2 g^2}{(2\pi)^4} \frac{1}{4z} \frac{(1-z)}{z} \frac{m}{\Lambda'(k_\perp^2)} \frac{M_\pi}{k_\perp^2} e^{-b'(k_\perp^2 - \Lambda'(0))} [\Gamma(0, b\Lambda'(0)) - \Gamma(0, b'\Lambda'(k_\perp^2))],$$

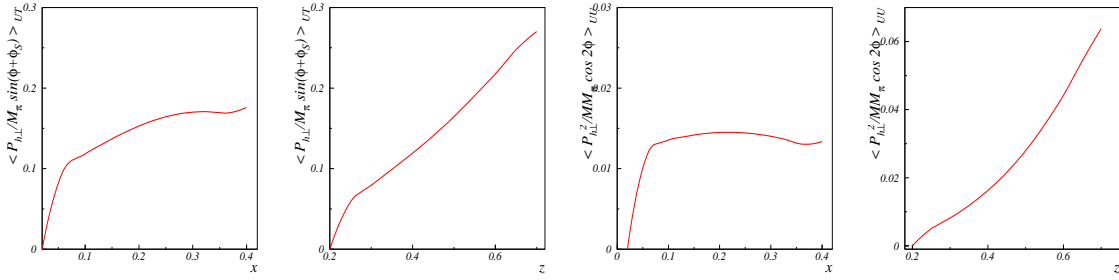
$\Gamma(0, z)$  is the incomplete gamma function and  $\Lambda'(k_\perp^2) = k_\perp^2 + \frac{1-z}{z^2} M_\pi^2 + \frac{\mu^2}{z} - \frac{1-z}{z} m^2$ . The average  $\langle k_\perp^2 \rangle = 1/b'$  is a regulating scale which we fit to the expression for the integrated unpolarized fragmentation function

$$D_1(z) = \frac{\mathcal{N}'^2 f^2}{4(2\pi)^2} \frac{1}{z} \frac{(1-z)}{z} \left\{ \frac{m^2 - \Lambda'(0)}{\Lambda'(0)} - [2b'(m^2 - \Lambda'(0)) - 1] e^{2b'\Lambda'(0)} \Gamma(0, 2b'\Lambda'(0)) \right\}$$

which is in good agreement with the distribution of Ref. [21]. In Fig. 1 the weighted the analyzing power,  $H_1^{\perp(1)}(z)/D_1(z)$ , is displayed. The resulting behavior is similar to a previous model ansatz proposed by Collins and calculated in Ref. [22]. The  $\cos 2\phi$  asymmetry of SIDIS is projected out of the cross section and depends on a leading



**FIGURE 1.** Left Panel:  $h_1^\perp \star H_1^\perp \cos 2\phi$  asymmetry. Right Panel: The weighted analyzing power  $H_1^{\perp(1)}(z)/D_1(z)$  as a function of  $z$ .



**FIGURE 2.** The  $\langle \sin(\phi + \phi_s) \rangle_{UT}$  asymmetry for  $\pi^+$  production as a function of  $x$  and  $z$ . The  $\langle \cos 2\phi \rangle_{UU}$  asymmetry for  $\pi^+$  production as a function of  $x$  and  $z$ .

double  $T$ -odd product,

$$\langle \frac{|P_{h\perp}^2|}{MM_\pi} \cos 2\phi \rangle_{UU} = \frac{8(1-y) \sum_q e_q^2 h_1^{\perp(1)}(x) z^2 H_1^{\perp(1)}(z)}{(1+(1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)}. \quad (2)$$

$UU$  indicates unpolarized beam and target and  $h_1^{\perp(1)}(z)$  is the weighted moment of the distribution function [6, 10]. For a transversely polarized target nucleon, the  $\sin(\phi + \phi_s)$  asymmetry[5, 11] can be similarly obtained yielding, the convolution of two chiral-odd structures,

$$\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \rangle_{UT} = |S_T| \frac{2(1-y) \sum_q e_q^2 h_1(x) z H_1^{\perp(1)}(z)}{(1+(1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)}. \quad (3)$$

The variable range to coincides with the HERMES kinematics [8]. In Fig. 2 the asymmetry of Eq. (3) for  $\pi^+$  production on a proton target is presented as a function of  $x$  and  $z$ , respectively indicating approximately a 10–15%  $P_{h\perp}/M_\pi$  weighted  $\sin(\phi + \phi_s)$  asymmetry. Also, in Fig. 3 the  $P_{h\perp}^2/(MM_\pi)$  weighted  $\cos 2\phi$  asymmetry of Eqs. (2) for  $\pi^+$  production on an unpolarized proton target is presented as a function of  $x$  and  $z$ , respectively indicating a few percent effect.

## Conclusion

A mechanism to generate the  $T$ -odd Collins fragmentation function that is derived from the gauge link has been considered. This approach complements the approach that was employed to generate the  $T$ -odd distribution functions,  $f_{1T}^\perp$  and  $h_1^\perp$  that fuel the Sivers and  $\cos 2\phi$  asymmetries. The derivation of  $H_1^\perp$  is consistent with the observation that intrinsic transverse quark momenta and angular momentum conservation are intimately tied with studies of transversity. Furthermore, this approach is interesting in that it does not suffer from the possible cancellation of the Collins effect cited in [23]. This effect is generated in the non-trivial phase associated with the gauge link operator [12, 13, 17, 9, 10, 24]. We have evaluated the analyzing power and predicted the  $P_{h\perp}/M_\pi$  weighted  $\sin(\phi + \phi_S)$  asymmetry at HERMES energies. Additionally, we predict that there is a non-trivial  $\cos 2\phi$  asymmetry associated with the asymmetric distributions of transversely polarized quarks inside unpolarized hadrons. Generalizing from these model calculations, it is clear that initial and final state interactions can account for leading twist  $T$ -odd contributions to SSAs. Using rescattering as a mechanism to generate  $T$ -odd distribution and fragmentation functions opens a new window into the theory and phenomenology of transversity in hard processes.

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